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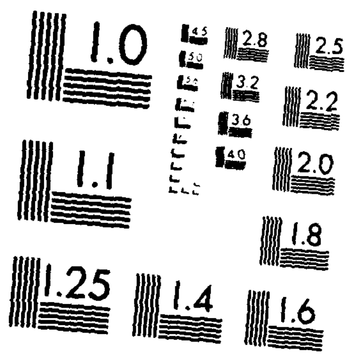

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Electrostatic Equations for Large Scale Plasma Simulation Studies

K. HAIN AND J. FEDDER

Geophysical and Plasma Dynamics Branch
Plasma Physics Division

July 19, 1984

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~~We derive~~ a set of equations for large scale simulation studies of plasma systems in the electrostatic approximation. The equations are written for a generalized geometry as well as for a dipole geometry which is suitable for the earth's magnetosphere.

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ELECTROSTATIC EQUATIONS FOR LARGE SCALE PLASMA SIMULATION STUDIES

I. INTRODUCTION

In recent years, global numerical simulation of plasma dynamics has become an area of active research interest. A large portion of this effort has been based on the equations of magnetohydrodynamics, MHD. The equations of MHD include a plasma continuity equation, a momentum equation, an energy equation, Maxwell's equations, and Ohm's law. These equations allow a simulation of the temporal evolution of a fluid plasma and the electromagnetic field. Perpendicular to the magnetic field the simulations maintain a balance between plasma forces and field forces, while parallel to the field the balance depends only on fluid quantities. The balance between plasma and field forces is responsible, in part, for the reliability and accuracy of the simulation results. In certain problems of interest the plasma has a relatively low temperature and the magnetic forces dominate the motion perpendicular to the field. This situation leads to difficulties in accurately computing the plasma forces and therefore the dynamics of the plasma. In such situations the difficulty can be alleviated by restricting the MHD equations to the so-called electrostatic approximation. In the electrostatic approximation one retains the hydrodynamic equations parallel to the magnetic field but perpendicular to the magnetic field balances plasma forces against $\underset{\sim}{J} \times \underset{\sim}{B}$, where $\underset{\sim}{B}$ is a known invariant magnetic field and $\underset{\sim}{J}$ is calculated from the difference between electron and ion velocities.

The purpose of this report is to derive a set of electrostatic equations which can be used to develop a simulation code for large scale low pressure plasma systems. This is done in a general coordinate

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system. The organization of the paper is as follows. In the Section II the meaning of the electrostatic approximation is discussed. In Section III, the physical equations are derived. In Section IV, the electrostatic equations are written for a general coordinate system. In Section V, the application of these equations to a plasma system in a dipole coordinate system appropriate for the earth's ionosphere-magnetosphere is presented. Finally, in Section VI we briefly summarize our results.

II. THE ELECTROSTATIC APPROXIMATION

The electrostatic approximation consists of four assumptions:

1) All forces are small compared to the magnetic force so that $\partial \underset{\sim}{B}/\partial t = 0$ and $\nabla \times \underset{\sim}{B} = 0$. In order for B not to change in time it is sufficient and necessary that the electric field, is the gradient of a scalar, i.e., $\underset{\sim}{E} = -\nabla\Psi$.

2) The current $\underset{\sim}{J}$ is given explicitly by the difference in the ion and electron velocities, i.e., $\underset{\sim}{J} = en(\underset{\sim}{V}_i - \underset{\sim}{V}_e)$. The requirement that $\nabla \cdot \underset{\sim}{J} = 0$ provides an equation for the electric potential Ψ.

3) The electrostatic potential Ψ is constant along magnetic field lines, i.e., the field lines are equipotentials.

4) In order to compute the velocities perpendicular to the magnetic field lines one uses the approximation $\underset{\sim}{E} + \underset{\sim}{V}_i \times \underset{\sim}{B} = 0$. This assumption is not necessary but greatly simplifies the analysis.

Within the context of these assumptions, i.e., the electrostatic approximation, we derive an appropriate set of equations for performing plasma simulations in a general coordinate system.

III. DERIVATION OF EQUATIONS

The momentum equations for the electrons and ions are, respectively,

$$-\frac{e}{m_e}(\mathbf{E} + \mathbf{V}_e \times \mathbf{B}) - \nu_{en}(\mathbf{V}_e - \mathbf{V}_n) - \nu_{ei}(\mathbf{V}_e - \mathbf{V}_i) = \mathbf{g}_e \tag{1}$$

$$\frac{e}{m_i}(\mathbf{E} + \mathbf{V}_i \times \mathbf{B}) - \nu_{in}(\mathbf{V}_i - \mathbf{V}_n) - \nu_{ie}(\mathbf{V}_i - \mathbf{V}_e) = \mathbf{g}_i \tag{2}$$

where $\mathbf{B}$ is the magnetic induction, $\mathbf{E}$ is the electric field, $\mathbf{V}_e$, $\mathbf{V}_i$, and $\mathbf{V}_n$ are the electron, ion, and neutral velocities, respectively, ν_{en} and ν_{ei} are the electron-neutral and electron-ion collision frequencies, ν_{in} and ν_{ei} are the ion-neutral and ion-electron collision frequencies, respectively, and $\mathbf{g}_\alpha$ is the total force (including inertia) acting on species α.

Equations (1) and (2) can be written in the form

$$-\mathbf{V}_{en} \times \mathbf{\Omega} - (\lambda\nu_{en} + \nu)\mathbf{V}_{en} + \nu\mathbf{V}_{in} = \mathbf{g}_e\lambda + \boldsymbol{\varepsilon} \tag{3}$$

$$\mathbf{V}_{in} \times \mathbf{\Omega} - (\nu_{in}/\lambda + \nu)\mathbf{V}_{in} + \nu\mathbf{V}_{en} = \mathbf{g}_i/\lambda - \boldsymbol{\varepsilon} \tag{4}$$

where

$$\mathbf{V}_{en} = \mathbf{V}_e - \mathbf{V}_n$$

$$\mathbf{V}_{in} = \mathbf{V}_i - \mathbf{V}_n$$

$$\boldsymbol{\varepsilon} = e(m_e m_i)^{-1/2}(\mathbf{E} + \mathbf{V}_n \times \mathbf{B})$$

$$\underset{\sim}{\Omega} = e\underset{\sim}{B}/(m_e m_i)^{1/2} \qquad \lambda = (m_e/m_i)^{1/2}$$

$$\nu = \lambda\nu_{ei} = \nu_{ie}/\lambda .$$

Eliminating the cross terms from Eqs. (3) and (4) one finds that

$$d_e \underset{\sim}{V}_{en} + \nu b \underset{\sim}{V}_{in} = -\lambda\nu_{en}\underset{\sim}{\varepsilon} + \underset{\sim}{\varepsilon} \times \underset{\sim}{\Omega}$$
$$-\lambda^2 g_e \nu_{en} - \nu(\lambda g_e + g_i/\lambda) + \lambda g_e \times \underset{\sim}{\Omega} \tag{5}$$

$$d_i \underset{\sim}{V}_{in} - \nu b \underset{\sim}{V}_{en} = (\nu_{in}/\lambda)\underset{\sim}{\varepsilon} + \underset{\sim}{\varepsilon} \times \underset{\sim}{\Omega}$$
$$- \; g_i/\lambda^2 \nu_{in} - \nu(\lambda g_e + g_i/\lambda) - g_i/\lambda \times \underset{\sim}{\Omega} \tag{6}$$

where

$$d_e = \Omega^2 + (\lambda\nu_{en} + \nu)^2 - \nu^2$$

$$d_i = \Omega^2 + (\nu_{in} + \nu)^2 - \nu^2$$

$$b = \nu_{in}/\lambda - \lambda\nu_{en} \text{ and } \Omega^2 = |\underset{\sim}{\Omega}|^2 .$$

Defining the quantity D

$$D = d_i d_e + \nu^2 b^2$$

one can solve for $\underset{\sim}{V}_{en}$ and $\underset{\sim}{V}_{in}$

$$\underset{\sim}{V}_{en} = \frac{1}{D}\{-(d_i\lambda\nu_{en} + \nu b\nu_{in}/\lambda)\ \underset{\sim}{\varepsilon} + (d_i - \nu b)(\underset{\sim}{\varepsilon} \times \underset{\sim}{\Omega})$$

$$-(\lambda^2 g_e\nu_{en}d_i - \nu b\ g_i\nu_{in}/\lambda^2) - \nu(d_i - \nu b)(\lambda g_e + g_i/\lambda)$$

$$+ (\lambda\ d_i g_e + \nu b\ g_i/\lambda) \times \underset{\sim}{\Omega}\ \} \tag{7}$$

and

$$\underset{\sim}{V}_{in} = \frac{1}{D}\{(d_e\nu_{in}/\lambda - \nu b\ \lambda\nu_{en})\underset{\sim}{\varepsilon} + (d_e + \nu b)(\underset{\sim}{\varepsilon} \times \underset{\sim}{\Omega})$$

$$-(g_i\nu_{in}d_e/\lambda^2 + g_e\nu b\ \lambda^2\nu_{en}) - \nu(d_e + \nu b)(\lambda g_e + g_i/\lambda)$$

$$-(g_i d_e/\lambda - g_e\nu b\lambda) \times \underset{\sim}{\Omega} \tag{8}$$

We now derive an expression for the current $\underset{\sim}{J}$ using Eqs. (7) and (8). We note that

$$\underset{\sim}{J} = en_e(\underset{\sim}{V}_i - \underset{\sim}{V}_e) = en_e(\underset{\sim}{V}_{in} - \underset{\sim}{V}_{en}) \tag{9}$$

so that

$$\underset{\sim}{J} = \sigma_p\ (\underset{\sim}{E} + \underset{\sim}{V}_n \times B) + \sigma_h(\underset{\sim}{E} \times \underset{\sim}{B}/B - B\underset{\sim}{V}_n)$$

$$+ \frac{\rho\lambda}{\Omega B}\{S_e\ \lambda^2 g_e\nu_{en} - S_i g_i\nu_{in}/\lambda^2 + \nu(S_e - S_i)(\lambda g_e + g_i/\lambda)$$

$$- (S_e\lambda g_e + S_i g_i/\lambda) \times \underset{\sim}{\Omega}\} \tag{10}$$

where

$$S_e = \frac{\Omega^2}{D} (d_i - \nu b)$$

$$S_i = \frac{\Omega^2}{D} (d_e + \nu b)$$

$$\sigma_p = (\rho/B^2)(S_e \nu_{en} \lambda^2 + S_i \nu_{in})$$

$$\sigma_h = (\rho/B^2)\Omega\lambda(S_i - S_e)$$

and $\rho = n_e m_i$ and $B = |\underset{\sim}{B}|$

In order to get an equation for the potential one has to first isolate the inertial terms. Neglecting electron inertia and defining

$$\underset{\sim}{g}_i = \frac{d\underset{\sim}{V}_i}{dt} - \underset{\sim}{f}_i \; ; \; \underset{\sim}{g}_e = - \underset{\sim}{f}_e/\lambda^2$$

one finds that

$$\begin{aligned} \underset{\sim}{J} - \sigma_p \underset{\sim}{E} - \sigma_h \underset{\sim}{E} \times \underset{\sim}{B}/B &= \sigma_p (\underset{\sim}{V}_n \times \underset{\sim}{B}) - \sigma_h \underset{\sim}{V}_n |B| \qquad (11) \\ &- \frac{\rho}{B\Omega} \{S_i d\underset{\sim}{V}_i/dt - S_i \underset{\sim}{f}_i - S_e \underset{\sim}{f}_e\} \times \underset{\sim}{\Omega} \\ &- \frac{\rho}{B\Omega\lambda} \{[S_i \nu_{in} + (S_i - S_e) \nu \lambda] d\underset{\sim}{V}_i/dt \\ &- [S_i \nu_{in} + (S_i - S_e) \nu \lambda] \underset{\sim}{f}_i + [S_e \nu_{en} \lambda^2 + (S_e - S_i) \nu \lambda] \underset{\sim}{f}_e\} \end{aligned}$$

We rewrite Eq. (11) using the following notation

$$T_{pi} = S_i \qquad\qquad T_{pe} = S_e$$

$$T_{hi} = \frac{S_i \nu_{in} + (S_i - S_e)\nu\lambda}{\Omega\lambda} \qquad T_{he} = \frac{S_e \nu_{en}\lambda^2 + (S_e - S_i)\nu\lambda}{\Omega\lambda}$$

so that one finally obtains

$$\begin{aligned} \underset{\sim}{J} - \sigma_p \underset{\sim}{E} - \sigma_h(\underset{\sim}{E} \times \underset{\sim}{B})/B &= \sigma_p(\underset{\sim}{V}_n \times \underset{\sim}{B}) - \sigma_h \underset{\sim}{V}_n B \\ &\quad - (\rho/B^2)\lfloor T_{pi}(d\underset{\sim}{V}_i/dt - \underset{\sim}{f}_i) - T_{pe}\underset{\sim}{f}_e \rfloor \times \underset{\sim}{B} \\ &\quad - (\rho/B)\lfloor T_{hi}(d\underset{\sim}{V}_i/dt - \underset{\sim}{f}_i) + T_{he}\underset{\sim}{f}_e \rfloor \end{aligned} \tag{12}$$

The total time derivative d/dt also contains all coriolis and centrifugal terms.

Using $\nabla \cdot \underset{\sim}{J} = 0$ and integrating along the fields with

$$E = -\nabla\Psi \; ; \quad V_i = (\underset{\sim}{E} \times \underset{\sim}{B})/|\underset{\sim}{B}|^2$$

one can derive the following two dimensional potential equation for Ψ

$$\begin{aligned} &\int dl\ \nabla \cdot \lfloor \sigma_p \nabla\Psi + (\rho/B) T_{pi} d(\nabla\Psi/B)/dt \rfloor \\ &+ \int dl\ \nabla \cdot \lfloor \{(-\sigma_h \nabla\Psi + (\rho/B) T_{hi} d(\nabla\Psi/B)/dt) \times \underset{\sim}{B}\}/B \rfloor \\ &= \int dl\ \nabla \cdot \lfloor \sigma_p(\underset{\sim}{V}_n \times \underset{\sim}{B}) \rfloor - \int dl\ \nabla \cdot \lfloor \sigma_h \underset{\sim}{V}_n B \rfloor \\ &+ \int dl\ \nabla \cdot \lfloor (\rho/B^2)\underset{\sim}{F}_p \times \underset{\sim}{B} \rfloor + \int dl\ \nabla \cdot \lfloor (\rho/B)\underset{\sim}{F}_h \rfloor \end{aligned} \tag{13}$$

where

$$\underset{\sim}{F}_p = T_{pi}\underset{\sim}{f}_i + T_{pe}\underset{\sim}{f}_e \qquad \underset{\sim}{F}_h = T_{hi}\underset{\sim}{f}_i - T_{he}\underset{\sim}{f}_e$$

This equation will be used in the subsequent analysis. The first integral represents the Pedersen conductance owing to collisions and the capacitance associated with plasma inertia. The next integral represents the analogous Hall terms. The first two terms on the right hand side are associated with collisional coupling to the neutral gas. They are, in many instances, the main driving terms.

One should remark also that the first integral in Eq. (13) must to be larger than the second integral for the potential equation to be diagonally dominant. By looking at the formulae for σ_p and σ_h one finds that the field line integral of the product of the plasma density and the Larmor frequency must be larger than the comparable integral of the collision frequency.

IV. GEOMETRY

We now derive an expression for the potential equation in a generalized geometry. An orthogonal coordinate system (x_1,x_2,x_3) is defined by the geometrical factors (h_1,h_2,h_3) such that the length element ds is given by

$$ds^2 = h_1^2\, dx_1^2 + h_2^2\, dx_2^2 + h_3^2\, dx_3^2 \tag{14}$$

We define

$$\partial_\alpha = \frac{1}{h_\alpha} \frac{\partial}{\partial x_\alpha} \tag{15}$$

so that

$$\nabla \cdot \underset{\sim}{A} = \frac{1}{g} \sum_\alpha \frac{\partial}{\partial x_\alpha} (h_{\alpha+1} h_{\alpha+2} A_\alpha); \quad g = h_1 h_2 h_3 \tag{16}$$

The covariant derivative of the velocity is given by

$$\sum_\alpha (V_\alpha \nabla_\alpha) V_\beta = \sum_\alpha \{(V_\alpha \partial_\alpha) V_\beta + c_{\beta\alpha} V_\alpha V_\beta - c_{\alpha\beta} V_\alpha^2 \} \tag{17}$$

with

$$c_{\beta\alpha} = \frac{1}{h_\beta} \partial_\alpha h_\beta \tag{18}$$

Since the electrostatic approximation assumes a vacuum magnetic field, one of the coordinates can be the field lines. Here x_3 is chosen. It follows then that

$$\nabla \cdot \underset{\sim}{B} = \frac{1}{g} \frac{\partial}{\partial x_3} (h_1 h_2 B_3) = 0 \tag{19}$$

which means

$$h_1 h_2 B_3 = f(x_1, x_2) \tag{20}$$

is a function of x_1 and x_2 only.

With the definition of

$$ds_3 = h_3\, dx_3 \tag{21}$$

the potential equation (Eq. (13)) can be written explicitly as

$$\frac{\partial}{\partial x_1} \left(\int \frac{h_2}{h_1} \sigma_p ds_3 \right) \frac{\partial}{\partial x_1}\Psi + \frac{\partial}{\partial x_2}\left(\int \frac{h_1}{h_2} \sigma_p ds_3 \right) \frac{\partial}{\partial x_2}\Psi$$

$$+ \frac{\partial}{\partial x_1}\left(\int \sigma_h ds_3 \right) \frac{\partial}{\partial x_2}\Psi - \frac{\partial}{\partial x_2}\left(\int \sigma_h ds_3 \right) \frac{\partial}{\partial x_1}\Psi$$

$$+ \frac{\partial}{\partial x_1} \int \left\{ h_2 \frac{\rho}{B} T_p \frac{d}{dt} \left(\frac{1}{B\, h_1} \frac{\partial}{\partial x_1} \Psi \right) ds_3 \right\} + \frac{\partial}{\partial x_2} \int \left\{ h_1 \frac{\rho}{B} T_p \frac{d}{dt} \left(\frac{1}{B\, h_2} \frac{\partial}{\partial x_2} \Psi \right) ds_3 \right\}$$

$$- \frac{\partial}{\partial x_1} \int \left\{ \frac{\rho}{B} T_h h_2 \frac{d}{dt} \left(\frac{1}{B\, h_2} \frac{\partial}{\partial x_2} \Psi \right) ds_3 \right\} + \frac{\partial}{\partial x_2} \int \frac{\rho}{B} T_h h_1 \frac{d}{dt} \left(\frac{1}{B\, h_1} \frac{\partial}{\partial x_1} \Psi \right) ds_3 \}$$

$$= \frac{\partial}{\partial x_1} \int B\, \sigma_p h_2 v_2^n ds_3 - \frac{\partial}{\partial x_2} \int B\, \sigma_p h_1 v_1^n ds_3$$

$$- \frac{\partial}{\partial x_1} \int B\, \sigma_h h_2 v_1^n ds_3 - \frac{\partial}{\partial x_2} \int B\, \sigma_h h_1 v_2^n ds_3$$

$$+ \frac{\partial}{\partial x_1} \int \frac{\rho}{B} F_p h_2 G_2 ds_3 - \frac{\partial}{\partial x_2} \int \frac{\rho}{B} F_p h_1 G_1 ds_3$$

$$+ \frac{\partial}{\partial x_1} \int \frac{\rho}{B} h_2 F_h G_1 ds_3 + \frac{\partial}{\partial x_2} \int \frac{\rho}{B} h_1 F_h G_2 ds_3 \tag{22}$$

It is the goal to separate geometrical quantities from fluid quantities. To this end we define normalized quantities at a point x_3^0. We define λ_α, B^0, and g^0 as follows:

$$\lambda_\alpha = \frac{h_\alpha}{h_\alpha^0} = \frac{h_\alpha(x_1, x_2, x_3)}{h_\alpha(x_1, x_2, x_3^0)} \tag{23}$$

$$B^0 = B(x_1, x_2, x_3^0)$$

$$g^0 = h_1^0 \; h_2^0 \; h_3^0 \tag{24}$$

so that

$$B = \frac{B^0}{\lambda_1 \; \lambda_2} \tag{25}$$

We also define the length elements

$$ds^{\alpha\beta} = h_1^\alpha \; h_2^\beta \; ds_3, \tag{26}$$

and split the total time derivative d/dt

$$\frac{d}{dt} = \frac{\partial}{\partial t} + (\underset{\sim}{V} \cdot \nabla), \tag{27}$$

and define

$$S_p = \sigma_p \; B^2 \qquad S_h = \sigma_h \; B^2 \tag{28}$$

With these definitions, the potential equation becomes

$$\frac{1}{g_0} \left\{ \frac{\partial}{\partial x_1}\left(\frac{h_2^0}{h_1^0 \; B_0^2} \int S_p ds^{13} \frac{\partial \Psi}{\partial x_1}\right) + \frac{\partial}{\partial x_2}\left(\frac{h_1^0}{h_2^0 \; B_0^2} \int S_p ds^{31} \frac{\partial \Psi}{\partial x_2}\right)\right\} \tag{29}$$

$$+ \frac{1}{g_0} \left\{\frac{\partial}{\partial x_1}\left(\frac{1}{B_0^2} \int S_h ds^{22} \frac{\partial \Psi}{\partial x_2}\right) - \frac{\partial}{\partial x_2}\left(\frac{1}{B_0^2} \int S_h ds^{22} \frac{\partial \Psi}{\partial x_1}\right)\right\}$$

$$+ \frac{1}{g_0} \{\frac{\partial}{\partial x_1} (\frac{h_2^0}{h_1^0 B_0^2} \int \rho \; T_p ds^{13} \frac{\partial^2 \Psi}{\partial x_1 \partial t}) + \frac{\partial}{\partial x_2} (\frac{h_1^0}{h_2^0 B_0^2} \int \rho \; T_p ds^{31} \frac{\partial^2 \Psi}{\partial x_2 \partial t})$$

$$- \frac{1}{g_0} \{\frac{\partial}{\partial x_1} (\frac{1}{B_0^2} \int \rho \; T_h ds^{22} \frac{\partial^2 \Psi}{\partial x_2 \partial t}) + \frac{\partial}{\partial x_2} (\frac{1}{B_0^2} \int \rho \; T_h ds^{22} \frac{\partial^2 \Psi}{\partial x_1 \partial t})\}$$

$$= - \frac{1}{g_0} \{\frac{\partial}{\partial x_1} [\frac{h_2^0}{B_0} \int \rho \; T_p (\underset{\sim}{V} \cdot \nabla) \frac{ds^{12}}{h_1 B} \frac{\partial \Psi}{\partial x_1}] - \frac{\partial}{\partial x_2} [\frac{h_1^0}{B_0} \int \rho \; T_p (\underset{\sim}{V} \cdot \nabla) \frac{ds^{21}}{h_2 B} \frac{\partial \Psi}{\partial x_2}]\}$$

$$+ \frac{1}{g_0} \{\frac{\partial}{\partial x_1} [\frac{h_2^0}{B_0} \int \rho \; T_h (\underset{\sim}{V} \cdot \nabla) \frac{ds^{12}}{h_2 B} \frac{\partial \Psi}{\partial x_2}] - \frac{\partial}{\partial x_2} [\frac{h_1^0}{B_0} \int \rho \; T_h (\underset{\sim}{V} \cdot \nabla) \frac{ds^{21}}{h_1 B} \frac{\partial \Psi}{\partial x_1}]\}$$

$$+ \frac{1}{g_0} \{\frac{\partial}{\partial x_1} (\frac{h_2^0}{B_0} \int S_p \; V_2^n ds^{12}) - \frac{\partial}{\partial x_2} (\frac{h_1^0}{B_0} \int S_p V_1^n ds^{21})\}$$

$$- \frac{1}{g_0} \{\frac{\partial}{\partial x_1} (\frac{h_2^0}{B_0} \int S_h V_1^n ds^{12}) - \frac{\partial}{\partial x_2} (\frac{h_1^0}{B_0} \int S_h V_2^n ds^{21})\}$$

$$+ \frac{1}{g_0} \{\frac{\partial}{\partial x_1} (\frac{h_2^0}{B_0} \int \rho \; Fp_2 ds^{12}) - \frac{\partial}{\partial x_2} (\frac{h_1^0}{B_0} \int \rho \; Fp_1 ds^{21})\}$$

$$+ \frac{1}{g_0} \{\frac{\partial}{\partial x_1} (\frac{h_2^0}{B_0} \int \rho \; Fh_1 ds^{12}) + \frac{\partial}{\partial x_2} (\frac{h_1^0}{B_0} \int \rho \; Fh_2 ds^{21})\}$$

The only integrals which are not cast in the standard form are the transport terms. We define

$$T_\alpha = - (\underset{\sim}{V} \cdot \nabla) V_\alpha = - (\underset{\sim}{V} \cdot \partial) V_\alpha - \sum_\beta (c_{\alpha\beta} V_\alpha V_\beta - c_{\beta\alpha} V_\beta^2) \tag{30}$$

using equation (4).

Furthermore, we note that

$$V_1 = - \frac{1}{B \; h_2} \frac{\partial \Psi}{\partial x_2} = - f \; h_1 \frac{\partial \Psi}{\partial x_2} \tag{31}$$

$$V_2 = \frac{1}{B\ h_1}\frac{\partial\Psi}{\partial x_1} = f\ h_2 \frac{\partial\Psi}{\partial x_1} \tag{32}$$

and define

$$u_1 = -\ f \frac{\partial\Psi}{\partial x_2} \tag{33}$$

$$u_2 = \ f \frac{\partial\Psi}{\partial x_1} \tag{34}$$

The u_1, u_2 are independent of x_3. It follows that

$$V_1\partial_1 + V_2\partial_2 = u_1 \frac{\partial}{\partial x_1} + u_2 \frac{\partial}{\partial x_2} \tag{35}$$

and

$$(V_1\partial_1 + V_2\partial_2)\Psi = 0 \tag{36}$$

since Ψ is constant along flow lines. With this Eq. (30) becomes

$$T_\alpha = -\ h_\alpha\left(u_1 \frac{\partial}{\partial x_1} + u_2 \frac{\partial}{\partial x_2}\right)u_\alpha - \sum_\beta \left(2\ c_{\alpha\beta} V_\alpha V_\beta - c_{\beta\alpha} V_\beta^2\right). \tag{37}$$

Defining the following integration elements

$$ds_{\gamma\delta}^{\alpha\beta} = c_{\gamma\delta}\, ds^{\alpha\beta}, \tag{38}$$

the transport terms can then be written in the form

$$T_1^p = -\frac{h_1^0}{B_0}\{\int \rho T_p ds^{31}\left(u_1 \frac{\partial}{\partial x_1} + u_2 \frac{\partial}{\partial x_2}\right)u_1$$

$$+ h_1^0 \int \rho T_p ds_{11}^{41} u_1^2 + 2\, h_2^0 \int \rho T_p ds_{12}^{32}\, u_1 u_2 + 2 \int \rho T_p v_3 ds_{13}^{31} u_1$$

$$- \frac{h_2^{0\,2}}{h_1^0} \int \rho T_p ds_{21}^{23} u_2^2 - \frac{1}{h_1^0} \int \rho T_p v_3^2 ds_{31}^{21}\} \qquad (39)$$

$$T_2^p = -\frac{h_2^0}{B_0}\{\int \rho T_p ds^{13}\left(u_1 \frac{\partial}{\partial x_1} + u_2 \frac{\partial}{\partial x_2}\right)u_2 \qquad (40)$$

$$+ h_2^0 \int \rho T_p ds_{22}^{14} u_2^2 + 2\, h_1^0 \int \rho T_p ds_{21}^{23} u_1 u_2 + 2\, u_2 \int \rho T_p v_3 ds_{23}^{13}$$

$$- \frac{h_1^{0\,2}}{B_0\, h_2^0} \int \rho T_p ds_{12}^{32} u_1^2 - \frac{1}{h_2^0} \int \rho T_p v_3^2 ds_{32}^{12}\}$$

$$T_1^h = -\frac{h_2^0}{B_0}\{\int \rho T_h ds^{22}\left(u_1 \frac{\partial}{\partial x_1} + u_2 \frac{\partial}{\partial x_2}\right)u_1 \qquad (41)$$

$$h_1^0 \int \rho T_h ds_{11}^{32} u_1^2 + 2\, h_2^0 \int \rho T_h ds_{12}^{23} u_1 u_2 + 2 \int \rho T_h v_3 ds_{13}^{22} u_1$$

$$- \frac{h_2^{0\,2}}{h_1^0} \int \rho T_h ds_{21}^{14}\, u_2^2 - \frac{1}{h_1^0} \int \rho T_h v_3^2 ds_{31}^{12}\}$$

$$T_2^h = -\frac{h_1^0}{B_0}\{\int \rho T_h ds^{22}\left(u_1 \frac{\partial}{\partial x_1} + u_2 \frac{\partial}{\partial x_2}\right)u_2 \qquad (42)$$

$$+ h_2^0 \int \rho T_h ds_{22}^{23} u_2^2 + 2\, h_1^0 \int \rho T_h ds_{21}^{32} u_1 u_2 + 2 \int \rho T_h v_3 ds_{23}^{22} u_2$$

$$- \frac{h_1^{0\,2}}{h_2^0} \int \rho T_h ds_{12}^{41} u_1^2 - \frac{1}{h_2^0} \int \rho T_h v_3^2 ds_{32}^{21}\} .$$

We define the quantities

$$E_{11} = \frac{1}{B_0^2} \int S_p ds^{13} \qquad E_{22} = \frac{1}{B_0^2} \int S_p ds^{31} \qquad E_{12} = \frac{1}{B_0^2} \int S_h ds^{22} \tag{43}$$

$$C_{11} = \frac{1}{B_0^2} \int \rho T_p ds^{13} \qquad C_{22} = \frac{1}{B_0^2} \int \rho T_p ds^{31} \qquad C_{12} = \frac{1}{B_0^2} \int \rho T_h ds^{22} \tag{44}$$

$$D_1^p = \frac{1}{B_0} \int S_p v_1^n ds^{21} \qquad D_2^p = \frac{1}{B_0} \int S_p v_2^n ds^{12} \tag{45}$$

$$D_1^h = \frac{1}{B_0} \int S_h v_1^n ds^{12} \qquad D_2^h = \frac{1}{B_0} \int S_h v_2^n ds^{21} \tag{46}$$

$$F_1^p = \frac{1}{B_0} \int \rho F p_1 ds^{21} \qquad F_2^p = \frac{1}{B_0} \int \rho F p_2 ds^{12} \tag{47}$$

$$F_1^h = \frac{1}{B_0} \int \rho \; F h_1 ds^{12} \qquad F_2^h = \frac{1}{B_0} \int \rho F h_2 ds^{21} \tag{48}$$

The potential equation for Ψ can then be written in the final compact form

$$\begin{aligned}
&\frac{1}{g_0} \left\{ \frac{\partial}{\partial x_1} \left(\frac{h_2^0}{h_1^0} E_{11} \frac{\partial \Psi}{\partial x_1} \right) + \frac{\partial}{\partial x_2} \left(\frac{h_1^0}{h_2^0} E_{22} \frac{\partial \Psi}{\partial x_2} \right) \right\} \\
&+ \frac{1}{g_0} \left\{ \frac{\partial}{\partial x_1} \left(E_{12} \frac{\partial \Psi}{\partial x_2} \right) - \frac{\partial}{\partial x_2} \left(E_{12} \frac{\partial \Psi}{\partial x_1} \right) \right\} \\
&+ \frac{1}{g_0} \left\{ \frac{\partial}{\partial x_1} \left(\frac{h_2^0}{h_1^0} C_{11} \frac{\partial^2 \Psi}{\partial x_1 \partial t} \right) + \frac{\partial}{\partial x_2} \left(\frac{h_1^0}{h_1^0} C_{22} \frac{\partial^2 \Psi}{\partial x_2 \partial t} \right) \right\} \\
&- \frac{1}{g_0} \left\{ \frac{\partial}{\partial x_1} \, C_{12} \frac{\partial^2 \Psi}{\partial x_2 \partial t} \right) - \frac{\partial}{\partial x_2} \left(C_{12} \frac{\partial^2 \Psi}{\partial x_1 \partial t} \right) \Big\}
\end{aligned} \tag{49}$$

$$= \frac{1}{g_0} \frac{\partial}{\partial x_1} \{h_2^0 [D_2^p + T_2^p + F_2^p - D_1^h + T_1^h + F_1^h]\}$$

$$- \frac{1}{g_0} \{\frac{\partial}{\partial x_2} [h_1^0 [D_1^p + T_1^p + F_1^p + D_2^h - T_2^h - F_2^h]\}$$

V. APPLICATION TO DIPOLE COORDINATES

For the electrostatic approximation we assume an undisturbed geomagnetic field which is taken to be a pure dipole field. Therefore, we use the appropriate dipole coordinate system (η, ϕ, σ) where

$$\eta = \frac{r}{\sin^2\theta} \; ; \; \phi; \; \sigma = \frac{\cos\theta}{r^2} \tag{50}$$

where r is the radius, ϕ the magnetic longitude, θ the magnetic colatitude. An orthogonal coordinate system is defined by the geometrical h factors, which we derive next.

We note that

$$\frac{\partial\eta}{\partial r} = \frac{1}{\sin^2\theta} \quad \frac{\partial\sigma}{\partial r} = -\frac{2\cos\theta}{r^3}$$

$$\frac{\partial\eta}{\partial\theta} = -\frac{2r\cos\theta}{\sin^3\theta} \quad \frac{\partial\sigma}{\partial\theta} = -\frac{\sin\theta}{r^2}, \tag{51}$$

which gives the Jacobian D

$$D = -\frac{1}{r^2\sin^3\theta}(1 + 3\cos^2\theta). \tag{52}$$

The inverse matrix is

$$\frac{\partial r}{\partial \eta} = \frac{\sin^4\theta}{1 + 3\cos^2\theta} \; ; \; \frac{\partial r}{\partial \sigma} = -\frac{2\, r^3 \cos\theta}{1 + 3\cos^2\theta}$$

$$\frac{\partial \theta}{\partial \eta} = -\frac{2}{r}\,\frac{\sin^3\theta\,\cos\theta}{1 + 3\cos^2\theta} \; ; \; \frac{\partial \theta}{\partial \sigma} = -\frac{r^2 \sin\theta}{1 + 3\cos^2\theta} \tag{53}$$

Using this matrix one finds that

$$h_\eta = \frac{\sin^3\theta}{(1 + 3\cos^2\theta)^{1/2}} \; ; \quad h_\phi = r\sin\theta ; \quad h_\sigma = \frac{r^3}{(1 + 3\cos^2\theta)^{1/2}} \, . \tag{54}$$

Furthermore it can be shown that

$$\partial_\eta r = \frac{\sin\theta}{(1 + 3\cos^2\theta)^{1/2}} \; ; \quad \partial_\sigma r = -\frac{2\cos\theta}{(1 + 3\cos^2\theta)^{1/2}} \, .$$

$$r\,\partial_\eta \theta = -\frac{2\cos\theta}{(1 + 3\cos^2\theta)^{1/2}} \; ; \quad r\,\partial_\sigma \theta = -\frac{\sin\theta}{(1 + 3\cos^2\theta)^{1/2}} \tag{55}$$

Since the geometry is independent of ϕ the $c_{\alpha\phi}$ are zero. After some algebra one finds the remaining c´s,

$$c_{\eta\eta} = -\frac{12\cos^2\theta(1 + \cos^2\theta)}{r\sin\theta\,(1 + 3\cos^2\theta)^{3/2}} \tag{56}$$

$$c_{\eta\sigma} = -\frac{6\cos\theta\,(1 + \cos^2\theta)}{r\,(1 + 3\cos^2\theta)^{3/2}} \tag{57}$$

$$c_{\phi\eta} = \frac{1 - 3\cos^2\theta}{r\sin\theta\,(1 + 3\cos^2\theta)^{1/2}} \tag{58}$$

$$c_{\phi\sigma} = -\frac{3\cos\theta}{r\,(1 + 3\cos^2\theta)^{1/2}} \tag{59}$$

$$c_{\sigma\eta} = \frac{3\sin\theta\,(1 + \cos^2\theta)}{r\,(1 + 3\cos^2\theta)^{3/2}} \, . \tag{60}$$

The coefficient for the gravity is

$$g_\eta = - g_{00}\left(\frac{r_0}{r}\right)^2 \frac{\sin\theta}{(1 + 3\cos^2\theta)^{1/2}} \; ; \; g_0 = g_{00}\left(\frac{r_0}{r}\right)^2 \frac{\cos\theta}{(1 + 3\cos^2\theta)^{1/2}} \qquad (61)$$

For high altitude magnetospheric problems one can set $\nu_{en} = 0$. Then with $\Omega_i = eB/m_i = \Omega\,\lambda$ and $b = (\nu_{in}/\lambda)\eta_{ie} = \nu_{ie}/\Omega_i = \nu/(\Omega_i\lambda^2)$ and $\omega_{ie} = \Omega_i + \eta_{ie}\nu_{in}$ one finds

$$T_p = \frac{\Omega_i\omega_{ie}}{\omega_{ie}^2 + \nu_{in}^2} \; ; \quad T_{pe} = \frac{\Omega_i\omega_{ie} + \nu_{in}^2}{\omega_{ie}^2 + \nu_{in}^2} \qquad (62)$$

$$T_h = \frac{\Omega_i\nu_{in}}{\omega_{ie}^2 + \nu_{in}^2} \; ; \quad T_{he} = \frac{\eta_{ie}\nu_{in}^2}{\omega_{ie}^2 + \nu_{in}^2} \qquad (63)$$

$$S_p = \rho\nu_{in}T_p ; \quad S_h = - \rho\nu_{in}T_h \qquad (64)$$

Furthermore we note that

$$\underset{\sim}{f}_i = \underset{\sim}{g} - \frac{1}{\rho}\nabla p_i \quad \underset{\sim}{f}_e = - \frac{1}{\rho}\nabla p_e \qquad (65)$$

which leads to

$$\underset{\sim}{F}_p = T_p\,\underset{\sim}{g} - \frac{1}{\rho}\left(T_p\nabla p_i + T_{pe}\nabla p_e\right); \quad \underset{\sim}{F}_h = T_h\,\underset{\sim}{g} - \frac{1}{\rho}\left(T_h\nabla p_i - T_{he}\nabla p_e\right). \qquad (66)$$

We choose the geomagnetic equator ($\sigma = 0$) as a reference plane. At the equator one has

$$h_1^0 = 1 \;\; ; \;\; h_2^0 = \eta \;\; ; \;\; h_3^0 = 1 \;\; ; \;\; g^0 = \eta \;\; ; \;\; B^0 = A/\eta^3 \qquad (67)$$

and

$$u_1 = -\frac{\eta^2}{A_0}\frac{\partial\Psi}{\partial\Phi}\ ;\ u_2 = \frac{\eta^2}{A_0}\frac{\partial\Psi}{\partial\eta}\ . \tag{68}$$

Introducing the earth's rotation ω, which means replacing v_ϕ by $v_\phi + \omega r \sin\phi$ or u_ϕ by $u_\phi + \omega$, one obtains for the transport terms

$$T_\eta^p = -\frac{1}{B_0}\Big\{ \int\rho\ T_p ds^{31}\Big(u_\eta \frac{\partial}{\partial\eta} + u_\phi \frac{\partial}{\partial\phi}\Big)u_\eta + \int\rho T_p ds^{41}_{\eta\eta} u_\eta^2$$

$$+ 2\int\rho T_p v_\sigma ds^{31}_{\eta\sigma} u_\eta - \eta^2 \int\rho T_p ds^{23}_{\phi\eta}\big(u_\phi + \omega\big)^2 - \int\rho T_p v_\sigma^2 ds^{21}_{\sigma\eta}\Big\} \tag{69}$$

$$T_\phi^p = -\frac{\eta}{B_0}\Big\{\eta \int\rho T_p ds^{13}\Big(u_\eta \frac{\partial}{\partial\eta} + u_\phi \frac{\partial}{\partial\phi}\Big)u_\phi$$

$$+ 2\int\rho T_p ds^{23}_{\phi\eta}\big(u_\phi + \omega\big)u_\eta + 2\int\rho T_p v_\sigma ds^{13}_{\phi\sigma}\big(u_\phi + \omega\big)\Big\} \tag{70}$$

$$T_\eta^h = -\frac{1}{B_0}\Big\{ \int\rho T_h ds^{22}\Big(u_\eta \frac{\partial}{\partial\eta} + u_\phi \frac{\partial}{\partial\phi}\Big)u_\eta + \int\rho T_h ds^{32}_{\eta\eta} u_\eta^2$$

$$+ 2\int\rho T_h v_\sigma ds^{22}_{\eta\sigma} u_\eta - \eta^2 \int\rho T_h ds^{14}_{\phi\eta}\big(u_\phi + \omega\big)^2 - \int\rho T_h\big(v_\sigma^2 + T_i + T_e\big) ds^{12}_{\sigma\eta}\Big\} \tag{71}$$

$$T_\phi^h = -\frac{\eta}{B_0}\Big\{ \int\rho T_h ds^{22}\Big(u_\eta \frac{\partial}{\partial\eta} + u_\phi \frac{\partial}{\partial\phi}\Big)u_\phi$$

$$+ 2\int\rho T_h ds^{32}_{\phi\eta}\big(u_\phi + \omega\big)u_\eta + 2\int\rho T_h v_\sigma ds^{22}_{\phi\sigma}\big(u_\phi + \omega\big)\Big\}\ . \tag{72}$$

The final equation can now be written as

$$\frac{1}{\eta}\frac{\partial}{\partial\eta}\left[\eta\, E_{\eta\eta}\frac{\partial\Psi}{\partial\eta}\right] + \frac{1}{\eta^2}\frac{\partial}{\partial\phi}\left[E_{\phi\phi}\frac{\partial\Psi}{\partial\phi}\right] \tag{73}$$

$$- \frac{1}{\eta}\left[\frac{\partial E_{\eta\phi}}{\partial\eta}\frac{\partial\Psi}{\partial\phi} - \frac{\partial E_{\eta\phi}}{\partial\phi}\frac{\partial\Psi}{\partial\eta}\right]$$

$$+ \left[\frac{1}{\eta}\frac{\partial}{\partial\eta}\left[\eta\, C_{\eta\eta}\frac{\partial^2\Psi}{\partial\eta\,\partial t}\right] + \frac{1}{\eta^2}\frac{\partial}{\partial\phi}\left[C_{\phi\phi}\frac{\partial^2\Psi}{\partial\phi\,\partial t}\right]\right]$$

$$+ \frac{1}{\eta}\left[\frac{\partial C_{\eta\phi}}{\partial\eta}\frac{\partial^2\Psi}{\partial\phi\,\partial t} - \frac{\partial C_{\eta\phi}}{\partial\phi}\frac{\partial^2\Psi}{\partial\eta\,\partial t}\right]$$

$$= \frac{1}{\eta}\frac{\partial}{\partial\eta}\left[\eta\left[D^p_\phi + T^p_\phi + F^p_\phi - D^h_\eta + T^h_\eta + F^h_\phi\right]\right]$$

$$- \frac{1}{\eta}\frac{\partial}{\partial\phi}\left[D^p_\eta + T^p_\eta + F^p_\eta + D^h_\phi - T^h_\phi - F^h_\phi\right],$$

where all symbols have been previously defined.

VI. SUMMARY

We have presented a set of equations for large scale simulation studies of plasma systems in the electrostatic approximation. The equations are written for a generalized geometry as well as for a dipole geometry which is suitable for the earth's magnetosphere.

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